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Climatic characterization and response of water resources to climate change in limestone areas: some considerations on the importance of geological setting

Di Matteo Lucio
University of Perugia, dimatteo@unipg.it

Valigi Daniela
University of Perugia, valigi@unipg.it

Cambi Costanza
University of Perugia, coscambi@unipg.it

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Di Matteo Lucio
Earth Sciences Department,
University of Perugia (Italy)
Piazza dell'Università, 1
06123 - Perugia (Italy)
+39 0755849694
dimatteo@unipg.it

Valigi Daniela
Earth Sciences Department,
University of Perugia (Italy)
Piazza dell'Università, 1
06123 - Perugia (Italy)
+39 0755840466
valigi@unipg.it

Cambi Costanza
Earth Sciences Department,
University of Perugia (Italy)
Piazza dell'Università, 1
06123 - Perugia (Italy)
+39 0755840465
coscambi@unipg.it

ABSTRACT

It is worldwide recognized and accepted that, in Southern Europe and the Mediterranean area in the last hundred years, the atmospheric temperature has risen by about 1°C, accompanied by a general decrease in precipitation. The trends detected in historical thermo-pluviometric series recorded in South/Central Italy show a general decrease in precipitation on an annual scale and a concentration of negative trends in the months from October to March. Analysis of the Standard Precipitation Index for the period 1951-2008 indicates higher frequency and duration of droughts in the last two decades: four prolonged dry periods (each lasting for up to three years) have been recorded since 1988, whereas only two main droughts have been identified in the four decades between 1951 and 1988. Climate change greatly influences the hydrogeological processes regulating both groundwater and surface water availability. If the present trends should continue, a total yield of 10-20% less than at present should be expected in the next 50 years. This work analyses the response of springs fed by karst/fractured limestone aquifers, extensively outcropping in Central Italy, taken as representative region, to climatic variations. It is shown how groundwater regime, the discharge of springs and their response to climate change depend to a great extent on the geologic and structural setting of the system. Some of the examined springs are "local systems" which represent "overflow" of a "deeper regional flow" feeding larger "base springs", often of poor quality (salty water), due to interactions with evaporite sediments of Triassic age. A dynamic groundwater divide, the position of which is greatly influenced by climate change, separates the recharge areas of base springs from those of local springs: as the piezometric surface is lowered, the watershed moves towards systems located at higher altitudes, producing a reduction in their recharge areas. Therefore, local springs connected to a base flow are more vulnerable to climate change than springs with recharge areas which do not feed a deep regional flow. The Bagnara and Lupa springs, taken as examples, have recharge areas with similar lithological, topographical and climate characteristics and similar mean discharges (about 120 l/s). In spite of this, only the discharge of the Bagnara spring, which is connected to a regional flow, fell dramatically during recent prolonged drought periods (e.g., 2001-2003 and 2006-2007). The results of the present research may be useful in studying hydrogeological processes in other limestone systems in climatically similar areas.

Categories and Subject Descriptors

J.2 Physical Sciences and Engineering: *Earth and atmospheric sciences*.

General Terms

Documentation, Verification.

Keywords

Climate change, drought, springs, limestone aquifers, Central Italy.

1. INTRODUCTION

It is now recognized and accepted worldwide that, in the last hundred years, the atmospheric temperature has risen (Trenberth et al., 2006; IPCC, 2007). According to the recent EC (2007), the mean annual temperature in Europe has increased by almost 1°C in the last century; this increase has been associated with a significant increase in precipitation in northern Europe and to higher frequency and duration of drought events in Southern Europe and the Mediterranean area, with a general decrease in precipitation. The historical data recorded in South/Central Italy match these statements (Maracchi et al., 2000; Brunetti et al., 2004; Di Matteo and Dragoni, 2006; Dragoni and Sukhija, 2008; Ducci and Tranfaglia, 2008; Polemio and Casarano, 2008; Brunetti et al., 2009; Longobardi and Villani, 2010). According to existing studies, all statistically significant trends detected in data recorded in Central Italy indicate a decrease in annual precipitation (with gradients ranging between -2 and -6 mm/year) and an increase in mean annual temperature (gradients up to +0.01°C/year) (Dragoni, 1998; Di Matteo et al., 2006). For the Euro-Mediterranean area, with the application of various regional models with resolutions of about 20-50 km, the European projects PRUDENCE (Déqué et al., 2005; Christensen and Christensen,

2007) and ENSEMBLES (Hewitt, 2005) have developed a set of climate simulations for the period 2071-2100 compared with those for 1961-1990. With reference to the IPCC SRES A2 scenario (continued demographic and economic growth and few technological changes), the increase in average temperature may vary between 2 and 5°C, with an increase during summer, whereas average annual precipitation will probably be reduced between 10% and 20% (Giorgi and Lionello, 2008).
Climate change greatly influences the hydrogeological processes regulating both groundwater and surface water availability. Within the framework of this general picture, the present work focuses on the fact that the response of a specific hydrogeological system to climate change closely depends on the geologic and structural setting of the system. Central Italy is taken as a representative region, being characterized by extensive outcrops of karst/fractured limestones, the aquifers of which supply several mountain springs with high-quality water located around the system (see Figure 1). After climatic characterization of the Central Apennine area on various time-scales (annual, seasonal and monthly), based on climate data for a 60-year period (1951-2008), the response of various springs to prolonged drought periods is analyzed in relationship to the geological setting of their recharge areas.

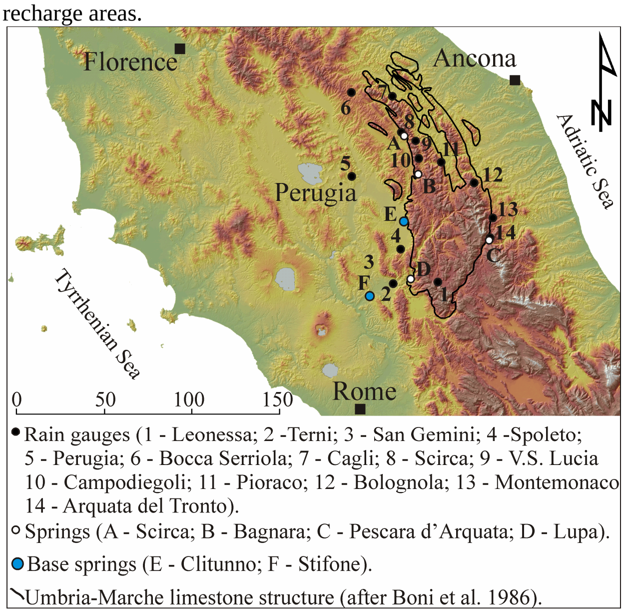

Figure 1. Location of Umbria-Marche limestone structure, with examined rain gauges and springs. Base map: shuttle topography mission DEM, cell size 90 m.

2. CLIMATE CHARACTERIZATION

Rainfall trends, on various time-scales, and the occurrence and duration of drought periods were analysed in order to investigate the influence of climate change on the groundwater yield of the Umbria-Marche limestone structure.
In order to meet criteria of reliability and uniformity, of the stations examined, only those which had been operating in the interval 1951-2008, and for which less than 10% data were missing, were chosen. Gaps in time series were filled by multiple regressions based on the best correlated data series (R^2>0.75) of the nearest rain gauges. The study area generally matches the Mediterranean climate profile, characterized by wet months from October to May and dry months during summer (June to September; Figure 2).

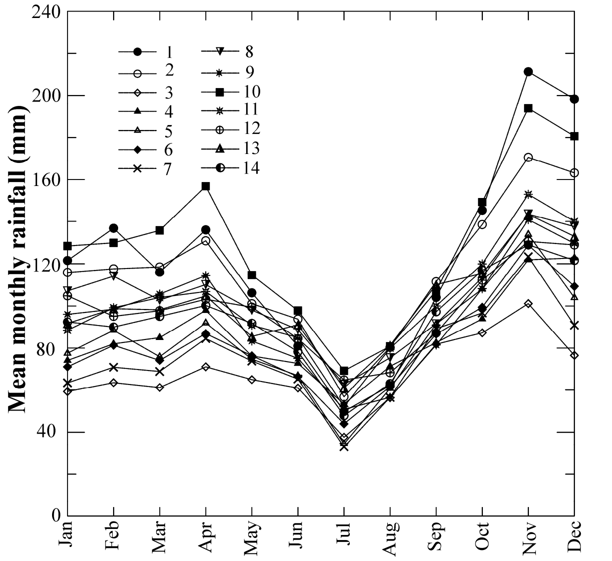

Figure 2. Mean monthly rainfall of examined rain gauges, numbered as in Figure 1.

All the 17 examined stations have a negative annual precipitation trend and for 14 of them (for locations, see Figure 1) trends are statistically significant according to the Mann-Kendall test (Mann, 1945; Kendall, 1975). Negative gradients range between about -3.2 and -9.8 mm/year (Table 1); the decrease in precipitation is generally higher in stations located at high altitudes or close to mountain areas. Analogous observations are reported by Ducci and Tranfaglia (2008) and Longobardi and Villani (2010), who studied climate change in Southern Italy and showed that the negative rainfall trends recorded in the Apennine area are greater in the main reliefs. This observation is particularly important, since most of the springs supplying drinkable water are fed by recharge areas located at high altitudes.
The Standardized Precipitation Index (SPI, McKee et al., 1993; Edward and McKee, 1997) was used to measure the magnitude and number of droughts occurring over the last six decades along the Umbria-Marche limestone hydrological system. In the SPI computation, the data are fitted to a gamma probability distribution and then transformed into a normal distribution, so that the mean SPI for the location and desired period is zero and the variance is one (Edwards and McKee, 1997). SPI computation requires long-term precipitation records. As reported by McKee et al. (1993) and recently by Naresh Kumar et al. (2009), at least 30 years of data are needed. Guttman (1999) suggested using at least 50 years of data to detect drought periods of 1 year or less. As stated by Wu et al. (2005): "the SPI values computed from different lengths of record are highly correlated and consistent when the gamma distributions of precipitation over the different time periods are similar". Instead, SPI values are significantly discrepant when distributions differ. In the present work, a record of 58 years was used (from 1951 to 2008). Precipitation data-sets from all the rain gauges listed in Table 1 were used to calculate the SPI on varying time-scales (3, 6, 9, and 12 months). SPI values above zero indicate wetter periods and values under 0 drier

periods. A drought event is defined when the SPI is continuously negative and reaches a value of -1.0 or less. When the SPI reaches -2.00 or less, an extremely dry period occurs.

According to Bordi et al. (2001), the SPI can be used as a tool in the historical reconstruction of drought events in Italy. Figure 3 shows the 12-months SPI for selected rain gauges located near some of the main springs of the Umbria-Marche limestone hydrological system, with continuous discharge measurements. The grey bars correspond to drought periods recorded at the same time in all stations. As can be observed for the last two decades, severe droughts (SPI< -1.5) common to all stations, occurred in the years 1988-1990, 1994-1995, 2001-2003 and 2006-2007. Conversely, only two main drought periods were identified in the four decades between 1951 and 1988 (1970-1971 and 1973-1975). It is interesting to note that the 12-months SPI reaches its lowest value (-3 and less) in the stations located to the east, beyond all the main reliefs of the Apennine chain and closer to the Adriatic Sea (see Figure 1).

Table 1. Statistical analysis of 6-month and 12-month rainfall trends (1951-2008). In bold significance levels (SL) lower than 95% (non-parametric Mann-Kendall test).

Rain gauges	Altitude m a.s.l.	6-months (Oct-Mar)		12-months (Jan-Dec)	
		trend (mm)	SL (%)	trend (mm)	SL (%)
Perugia	493	-1.74	**94.60**	-3.19	98.30
Bocca Serriola	730	-4.07	99.80	-7.09	99.98
Scirca	750	-4.50	98.00	-6.81	98.70
Cagli	280	-5.45	99.97	-7.87	99.95
Campodiegoli	507	-5.56	99.81	-8.73	99.96
V.S. Lucia	664	-3.71	98.20	-7.08	99.94
Pioraco	441	-4.75	99.87	-6.54	99.95
Bolognola	1070	-6.78	99.97	-9.77	99.98
Montemonaco	987	-3.35	99.29	-5.32	99.87
Arquata del Tronto	720	-3.01	97.60	-3.81	98.93
Leonessa	974	-6.39	98.80	-7.27	98.70
Spoleto	317	-2.74	**92.20**	-4.95	99.53
Terni	170	-3.52	97.82	-5.50	99.96
San Gemini	337	-3.66	98.5	-6.41	99.89

In view of the fact that, in the study area and in general in Central Italy, the main wet seasons are autumn and, to a lesser extent, spring (Figure 2), precipitation trend analysis was performed on various time-scales (3, 6 and 12 months). This analysis was run to verify whether negative precipitation trends are concentrated in the rainy seasons, representing the main recharge periods. Results showed that, on the 3-month scale, the trends are not always significant, whereas all the stations except two have highly significant trends for the 6-months period from October to March (Table 1).

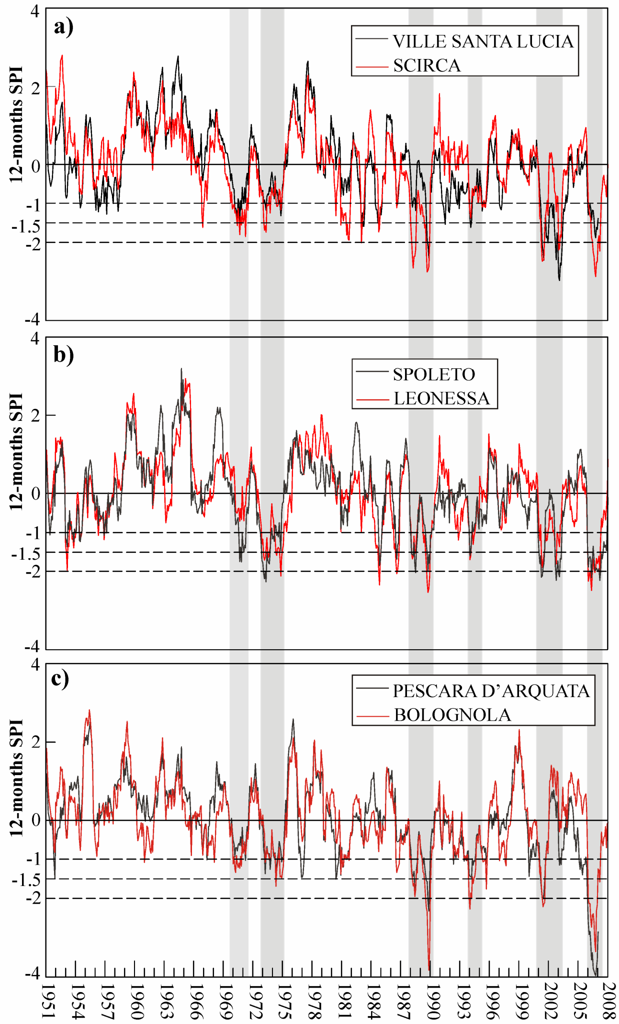

Figure 3. 12-month SPI time-scale for areas of Scirca and Bagnara springs (a), Pescara d'Arquata spring (b) and Lupa spring (c).

3. RESPONSE OF MOUNTAIN SPRINGS TO CLIMATE CHANGE

4.1 Geological and hydrogeological characteristics

The study area known as the Umbria-Marche Apennines is a compressive Miocene/Pliocene arc-shaped fold-and-thrust belt, with eastward vergence and convexity, later affected by Quaternary extension (Colacicchi and Pialli, 1967; Passeri, 1971; Barchi and Lavecchia, 1986; Ciaccio et al., 2005). The rocks belong to the Umbria-Marche sequence, consisting of Jurassic–Miocene carbonates and marls, in which fractured and/or stratified limestones host aquifers separated from each other by marl aquicludes. The stratigraphic sequence lies on Upper Triassic evaporites (anhydrite and dolomite). The main aquifers are located in the Lower Jurassic Calcare Massiccio Formation (fractured and karstified, highly permeable shelf limestone) and in the Lower Cretaceous Maiolica Formation (stratified and fractured pelagic limestone). Aquifers with slightly lower yields are located in the Upper Cretaceous Scaglia *s.l.* Formation (stratified and fractured pelagic limestone and marly limestone). The aquifer systems are separated by aquicludes made up of marl and clay with low or very low permeability (Rosso Ammonitico, Marne a Fucoidi and Scaglia Variegata and Cinerea Formations). Another impervious limit is represented by the thrust system bounding the chain to the east, with which splays and back-thrust structures are often associated.

The Umbria-Marche Sequence contains two main groundwater circuits, with substantially different chemical characteristics. The upper one lies in the Cretaceous Formations (Maiolica and Scaglia *s.l.*) and the lower one in the Calcare Massiccio (base aquifer). The water of the base aquifer is much saltier than that of the upper one, due to the higher solubility of Calcare Massiccio and to interactions with evaporite deposits. The water of the main springs fed by deeper groundwater circulation in Central Italy (Clitunno and Stifone springs) has salinity and electric conductivity values ranging between 0.8-2.7 g/l and 780-3900 µS/cm respectively, with high content of sulfates (340-420 mg/l) (Frondini, 2008; Di Matteo et al., 2009). Figure 1 shows the location of these springs.

The main mountain springs used for drinking water purposes are fed by the upper groundwater circuit: groundwater emerges at the contact between the Marne a Fucoidi and Maiolica Formations, conditioned by the main thrusts and back-thrusts. Due to the normal faults and/or hidden back-thrusts, the Maiolica aquifer may interconnect with that of the Scaglia *s.l.*. In other cases, normal faults allow hydraulic connections between the base aquifer and the Maiolica aquifer. As will be illustrated in the next sections, the geological-structural settings influence the relationships between the upper groundwater circuit and the deep regional flow, especially during prolonged periods of drought.

4.2 Analysis of springs discharge

The recharge areas of mountain springs in Central Italy, being located in mountain areas where there are no pumping wells, are virtually unaffected by human activity, so that analysis of spring discharges is useful tool in understanding the response of a certain hydrogeologic system to prolonged drought conditions. Fiorillo and Guadagno (2010) recently investigated the relationships between SPI and spring discharges of three karst springs in the Apennines of Southern Italy. The best correlation occurs for a time-scale of 9 months for the Serino group and 12 months for the Caposele and Cassano groups.

For information on the reaction of springs to drought periods, four systems for which daily discharge data series are available were examined (Scirca, Pescara di Arquata, Bagnara and Lupa springs). The former two are the only springs with long and continuous records going back to 1942 and 1960, respectively. The records of the Pescara d'Arquata spring were used to understand the response of the hydrogeologic system to rainfall trends observed in the nearest rain gauges (Montemonaco and Arquata del Tronto). The discharge data for Scirca are affected by uncertainty due to the fact that, for high discharge values, there is an overflow which is not measured (Angelini, 1997). Consequently, discharge peaks and mean discharge are practically unknown. Nevertheless, comparisons between the adjusted and measured hydrographs reported by Angelini (1997) show that discharges of under about 200 l/s are reliable. The data from Scirca were therefore used to define the trend for the periods with discharge values lower than 200 l/s (generally from June to September). As the data series of the other springs are not continuous, none of them could be used to analyse discharge trends monthly, seasonal or annual time-scales or study relationships between spring discharges and SPI, computed on different time-scales.

Figure 4 shows the monthly discharge data of the Pescara d'Arquata spring plotted on the same time-scale as the 6-month and 12-month SPI (data from Arquata del Tronto rain gauge). The lowest discharge values correspond to the lowest 12-month SPI values, but are shifted with respect to the lowest 6-month SPI. This indicates that the monthly discharge of this spring depends on the precipitation during the previous 12 months. The most severe droughts detected by SPI analysis (1970-1971, 1973-1975, 1988-1990, 1994-1995, 2001-2003 and 2006-2007) correspond to the lowest spring discharges.

The Mann-Kendall test performed on discharge data confirmed that there are significant negative discharge trends, on both an annual scale (-2.4 l/s/year) and for the 6-month interval from November to April (-2.3 l/s/semester), which corresponds to the main recharge period.

Statistical analysis on the Scirca data was applied to detect possible trends for the June-September period, corresponding to the period of minimum discharge. The Mann-Kendall test revealed a highly significant negative trend of about -0.4 l/s/4 months.

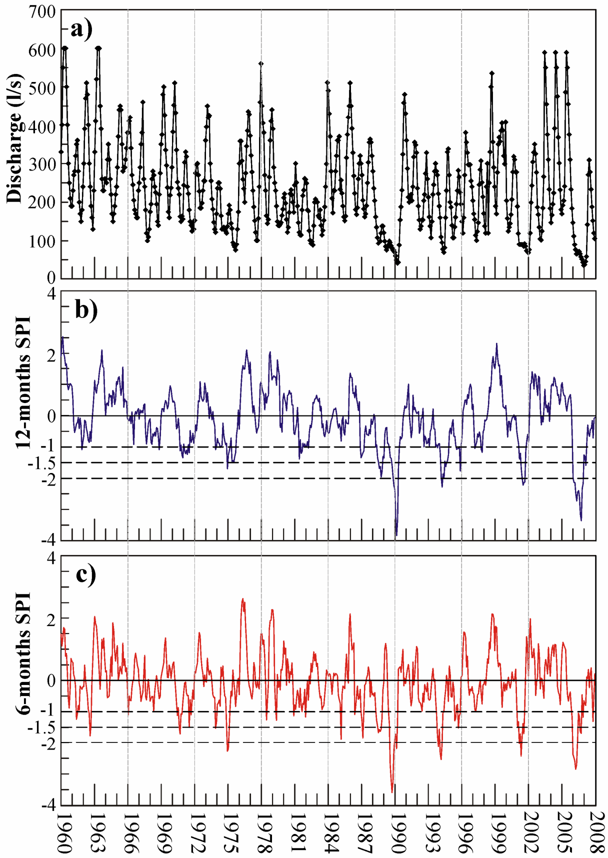

Figure 4. Monthly discharge hydrograph of Pescara d'Arquata spring. a) 12-month SPI; (b) 6-month SPI; (c) Arquata del Tronto rain gauge.

4.3 Response of mountain springs during prolonged drought periods

Two of the four selected springs, Bagnara and Lupa, were taken as examples to show how the geological-structural setting influences the reaction of limestone aquifers to drought. These springs were chosen because they have recharge areas with similar lithological, topographical and climatic characteristics and similar mean discharges (about 120 l/s). Figure 5 shows their discharge hydrographs over the last 20 years: only the Bagnara discharge is shown to have fallen close to nil three times, corresponding with the main droughts (see Figure 2). Conversely, the minimum discharge of the Lupa, which also corresponds to the most severe drought, never fell below about 40 l/s (2006-2007).

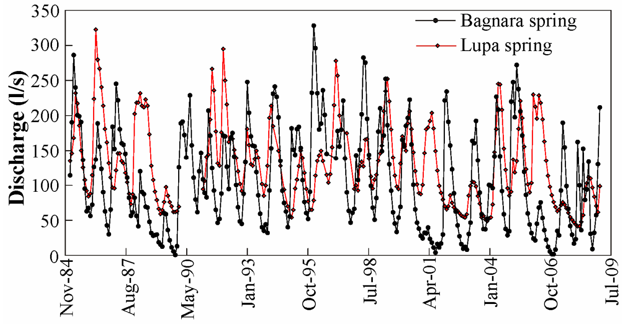

Figure 5. Discharge hydrographs of Bagnara and Lupa springs (January 1985-December 2008).

The different response to drought can be explained by analysing the structural setting of the two springs. The Lupa is fed mainly by the upper aquifer of the Maiolica Formation interconnected with the Scaglia s.l., and its recharge area is clearly defined by the Rosso Ammonitico outcrop (aquiclude), which represents a physical boundary. Instead, according to Cambi and Dragoni (2000), the recharge area of Bagnara is interconnected with the deep regional flow fed by the base aquifer: thus, it may be considered as the "overflow" of a complex groundwater circuit which feeds both the spring and the regional flow directed towards the base springs.

The recharge area of the Lupa, the extent of which is constant, is about 7 km2 wide, whereas that of Bagnara is defined by a dynamic piezometric divide which moves horizontally as the water table falls or rises, so that the size of the recharge area may change. The position of this dynamic divide, which is greatly influenced by climate change, separates the recharge area of base springs from that of Bagnara: as the piezometric surface falls, the watershed moves towards Bagnara (located at higher altitude), producing a reduction in its recharge area.

Figure 6 shows the conceptual schemes of both springs, derived from their geologic cross-sections, highlighting the differences between the two. For Bagnara during drought periods, which cause lowering of the water table, the discharge falls not only because the water table drops, but also because the recharge area shrinks. Instead, since the recharge area of Lupa remains unchanged, the reduction in discharge is only due to lowering of the water table.

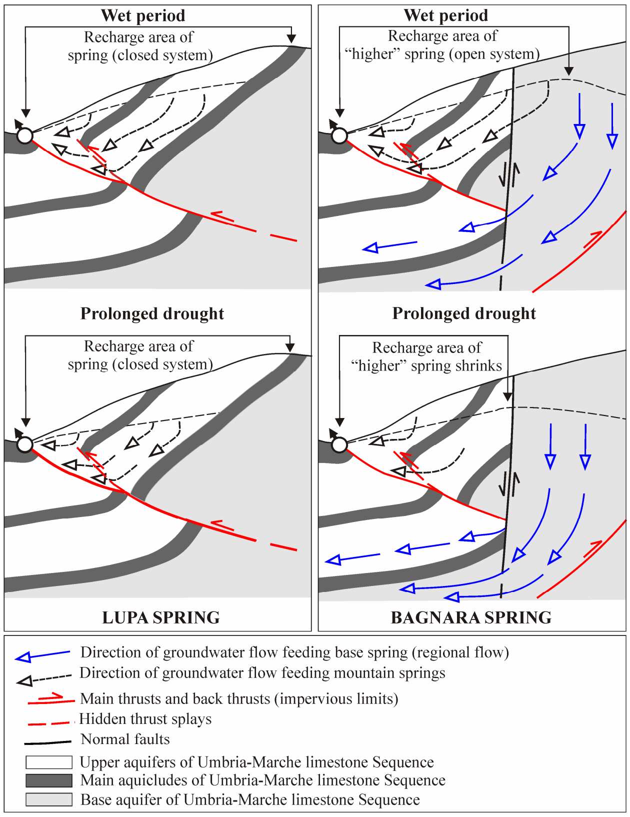

Figure 6. Conceptual schemes (not to scale) illustrating groundwater circulation feeding Lupa and Bagnara springs.

The different behaviour of the two systems is clear when we analyse the depletion curves of the springs during particularly severe droughts. Figure 7 shows depletion curves (daily data) recorded during the last two severe droughts detected in Central Italy (2003 and 2007). The entire recession phase of the Lupa fits the equation of Maillet (1905):

$$Q_t = Q_o \cdot e^{-\alpha t} \qquad 1)$$

where:

Q_t – discharge at time t (l/s)

Q_o – initial discharge at time t_o (l/s)

α – depletion coefficient (day^{-1})

Although equation (1) was developed by Maillet for porous media, it has also been widely applied to fractured systems, which may be considered – on suitable scales – as an equivalent porous media (Long et al., 1982; Bear, 1993; Bonacci, 1993). The Maillet depletion coefficients for the two periods of analysis range between -0.005 and -0.003/day-1 for 2003 and 2007, respectively (correlation coefficients of about 0.99). As previously shown, the Lupa is the only outflow of its hydrogeological system (closed system): therefore, the Maillet equation, which was developed to describe the depletion curves of systems having a single outflow, can properly describe its recession phases.

As Figure 7 shows, the Maillet equation describes the depletion curves for Bagnara approximately in the first half of the recession phase (α = -0.012 and -0.014/day^{-1} for 2003 and 2007, respectively; correlation coefficients about 0.99).

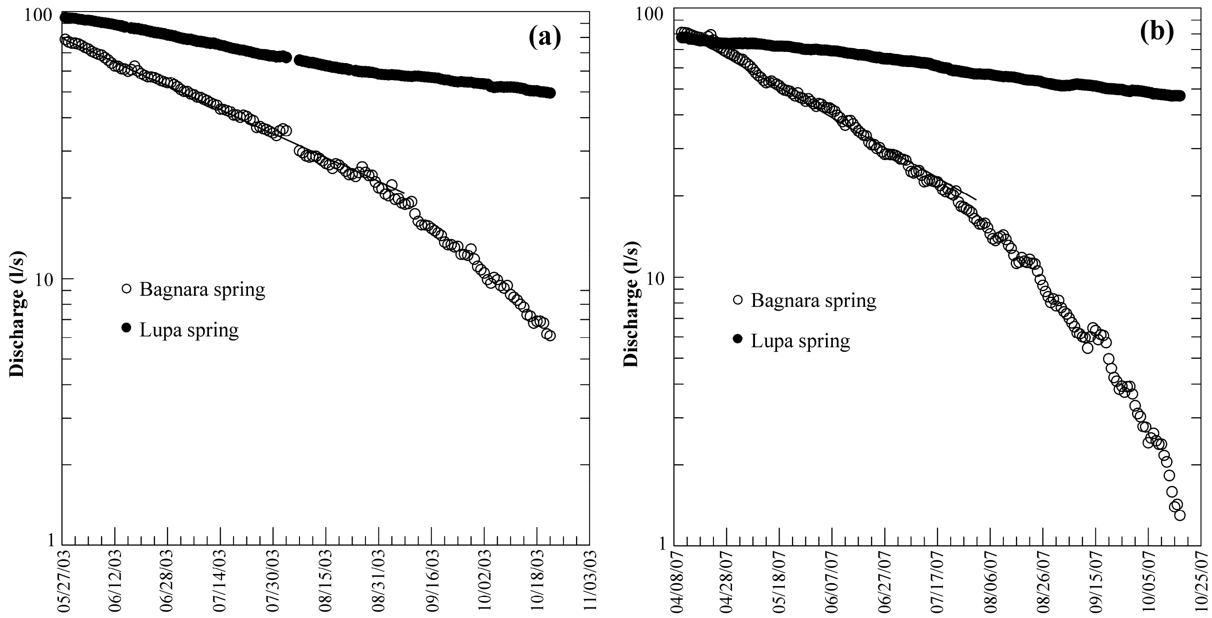

Figure 7. Depletion curves of Bagnara and Lupa springs during last two drought periods: (a) 2001-2003; (b) 2006-2007. Data from ARPA Umbria.

In the second part of the curves, the decrease in discharge becomes much faster, with final discharges approaching nil. The different behaviour of the two springs is due to the fact that the recharge area of Bagnara shrinks more and more as the water table falls during a drought. In the first stage of the recession, the portion of aquifer feeding the base flow is significantly smaller than that feeding the spring, so that the depletion curve follows the Maillet equation quite well, and there is no evidence of the effects of the lower outflow (Figure 6). In the final stages of recession, the aquifer portion feeding the base flow becomes larger, so that the effect of the second (lower) outflow becomes more evident and the depletion curve no longer follows the Mailett equation (Figure 6).

4. CONCLUSIONS

This work was based on analysis of precipitation and discharge data sets recorded in and around the mountain area of the Umbria-Marche Apennines (Central Italy). The 12-month SPI indicates that the frequency and intensity of droughts is increasing, since four severe droughts have occurred over the last 20 years and only two in the 40 years previously. The minimum SPI values (-3 and less) were detected in stations located to the east, beyond all the main reliefs of the Apennine chain and closer to the Adriatic Sea. According to the non-parametric Mann-Kendall test, a negative annual precipitation trend is occurring, with a general decrease in rainfall during the 6-month interval from October to March, corresponding to the main recharge period. The decrease in mean annual and seasonal precipitation greatly influences the hydrological cycle.

The effects of recharge reduction are evident in the monthly discharge trends of mountain springs, for which continuous discharge gauge recordings are available (Pescara d'Arquata and Scirca). The significance of these trends were examined with the Mann-Kendall test. Analysis of the Pescara d'Arquata spring showed significant negative discharge trends, on both an annual scale (-2.4 l/s/y) and during the 6-month interval from November to April (-2.3 l/s/semester). The Scirca shows a highly significant negative trend of about -0.4 l/s/4-months (June to September). With respect to the SPI values, the monthly discharge of the Pescara d'Arquata depends on precipitation throughout the previous 12 months, rather than on precipitation in shorter antecedent periods.

In light of the fact that the frequency and intensity of droughts are intensifying, it is important to understand how mountain springs, which are one of the main sources of drinkable water in this area, react to droughts. The results obtained in the present study show how, in limestone systems greatly affected by compressive and distensive tectonics, the reaction of springs to droughts depends on their geological setting. Two springs (Lupa and Bagnara), taken as representative of the Umbria-Marche Apennines, were studied by analysis of their recession curves during the last two droughts (2001-2003 and 2006-2007). This analysis showed that the response to drought of springs characterized by well-defined recharge areas (closed systems), such as the Lupa, is less severe than that of "open systems" interconnected with a deep regional flow (Bagnara). This means that, in times of drought, when the water table falls significantly, the discharge of springs like Bagnara decreases faster than that of ones like Lupa.

The results of the present research may be useful in studying hydrogeological processes in other limestone systems in climatically similar areas. Therefore, the writers would like to encourage others to investigate other similar systems, to better quantify the response of springs during prolonged droughts.

5. ACKNOWLEDGEMENTS

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